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MAGMATIC DIFFERENTIATION IN HAWAII

REGINALD A. DALY
Massachusetts Institute of Technology, Boston, U.S.A.

INTRODUCTION

Though the Hawaiian Islands are largely basaltic, it is already apparent that they contain igneous types of considerable petrographic diversity. The species so far discovered range from ultra-femic basalts and intrusive porphyry, with less than 46 per cent of silica and less than 2 per cent of alkalies, to the phonolitic trachyte of western Hawaii, with 62 per cent of silica and more than 13 per cent of alkalies. No sediments of the ordinary silicious kinds appear to enter into the composition of the islands or of their basement. Acid crystalline rocks of the gneissic or granitic order

also seem to play no rôle in the petrogenesis of the archipelago. Hence, some of the chief complications in the history of igneous magmas which have invaded the continental plateaus, that is, complications due to the assimilation of such highly varied country-

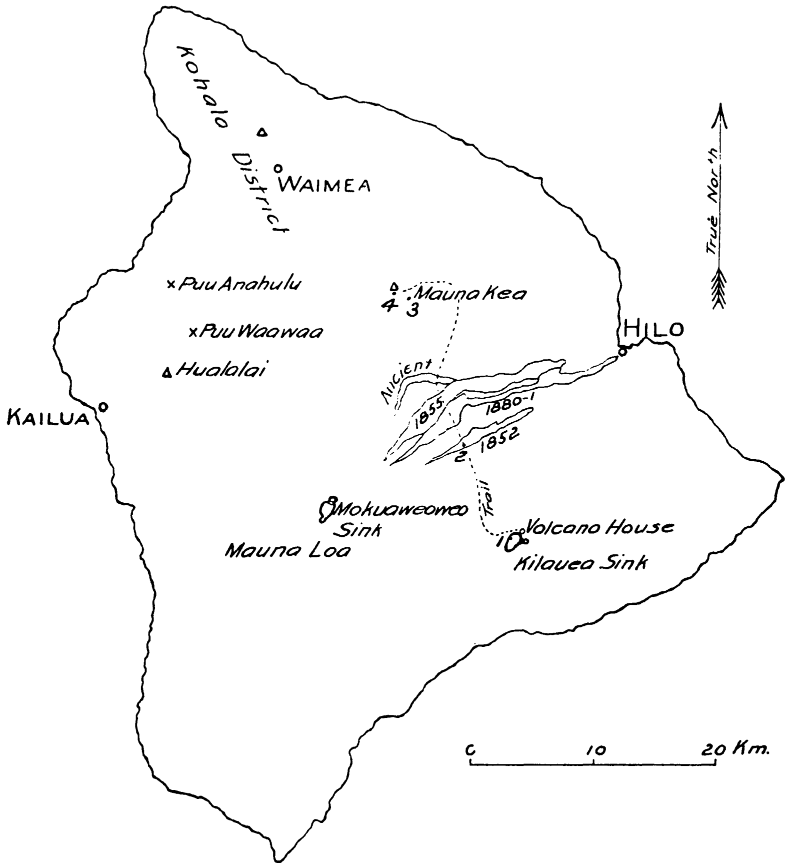

FIG. 1.—Locality map, showing positions of some of the dated lava flows in Hawaii; also original localities of specimens chemically analyzed (dots numbered 1 to 4): 1, gabbro of Uwekahuna laccolith; 2, olivine basalt of 1852 flow; 3, andesitic basalt; 4, trachydolerite.

rocks, here seem to be absent. This relative simplicity of conditions makes the petrogenesis of a deep-sea archipelago worthy of attention quite independently of its own intrinsic importance. The problem of origin here becomes largely, though not altogether,

a matter of pure differentiation. An inspection of the results so far attained in Hawaiian petrography clearly suggests the nature of the local primitive magma, namely, basalt, and shows the march of magmatic differentiation in the main island, from that parent species to the less voluminous rock-types which have so far been discovered.

The first part of this paper is devoted to a description of rock-types forming part of a collection made by the writer in 1909. From the facts won in that reconnaissance, and from those already published in the writings of J. D. and E. S. Dana, of Lyons, Phillips, Silvestri, Cohen, Möhle, Maxwell, C. H. Hitchcock, Brigham, Dutton, Cross, and others, an induction has been made as to the probable origin of the rock species in Hawaii. A brief statement of the reasoning on which this tentative conclusion is based occupies the second part of the paper.

The four new rock analyses and the analysis of phenocrystic olivine were made by Mr. G. Steiger, chemist of the United States Geological Survey. For these excellent data the writer's sincere thanks are due to him, and to Dr. G. O. Smith, the Director of the Survey, who generously acceded to the request that this work should be undertaken by the able experts of the government laboratory.

SPECIAL PETROGRAPHY

Porphyritic gabbro of the Uwekahuna laccolith.—About two hundred meters north of the Uwekahuna triangulation station, the western wall of the Kilauean sink exhibits a patch lighter in color than the average rock in the cliff. This patch is visible from the Volcano House and the writer made an early visit to this part of the sink. (See locality marked "1" in Fig. 1.) Nearing the place, it was observed that the light-tinted rock was more massive than the lavas above and below it. Large blocks of the rock had fallen from the cliff and many were plainly seen to have been derived from the lighter-colored mass, which was gabbroid in habit. With a little trouble the writer was able to scale the cliff for the vertical distance of about 20 meters, necessary to reach the lower contact. There the gabbroid rock showed a distinctly chilled phase in a contact shell several decimeters in thickness.

The upper contact was quite inaccessible, by ordinary climbing, though it might, perhaps, be reached with the aid of a rope let down from the top of the cliff. However, the coarse grain of the holocrystalline rock and the relation of the mass to the overlying ash-beds show without question that it is intrusive. The section given in the cliff is that of a laccolith, with a width of 160 meters and a maximum thickness of about 20 meters. The ash-beds above are uparched and conformable to the upper surface of the laccolith, except at the southern end, where they are cut across at a low angle by the gabbro. The massive lava flows overlying the ash beds are little, or not at all, deformed by the intrusion. Some of the upper flows may be younger than the laccolith, but it is possible that all the overlying flows are the older and that the lack of deformation in them is due to the lateral crowding and condensation of the loose ash-beds by the laccolithic magma.

The gabbroid body may conceivably represent the crystallized product of a subterranean lava stream of great length, but its deformation of the overlying ash-beds is characteristic of laccolithic intrusion and it seems just to describe the mass as a true laccolith.

The intrusive rock is dark gray in color, and slightly porous. It is porphyritic, with phenocrysts of olivine. These are so numerous that the rock appears, at first glance, to be somewhat coarsely granular. In the hand-specimen the phenocrysts appear roundish, and only rarely idiomorphic. Some of them are of the usual olive-green color, but most are iridescent on the surfaces of fracture, with the beautiful blue, green, and bronze tints of a peacock's feather. Though the rock in general is extremely fresh, this iridescence seems to be due to an incipient alteration of the olivine to serpentine, which is mixed with numerous, minute grains of iron ore.

Under the microscope, the idiomorphism of the nearly colorless, pale brownish olivine is more clearly manifest. It occurs in individuals reaching 4 mm. or more in length. The ground-mass is composed of plagioclase, augite, ilmenite, and magnetite; the chemical analysis of the rock shows that a little apatite must be present, but not a single crystal of it was demonstrable in the thin section. The ground-mass varies irregularly from the hypidio-

morphic-granular to the diabasic. The thin-tabular plagioclase, reaching 1 mm. in longest diameter, seems to be throughout the basic labradorite, $Ab_2\ An_3$. The pale brownish augite has normal habit, the major diameters reaching 0.8 or 1.0 mm. There is nothing unusual about the minerals of this rock and further descriptive details are superfluous.

An analysis of the rock, by Mr. G. Steiger, gave the result shown in col. 1 of Table I.

TABLE I

	1	1a	2
SiO_2	46.59	.777	48.13
TiO_2	1.83	.023	.87
Al_2O_3	7.69	.075	6.50
Fe_2O_3	2.20	.014	2.01
Cr_2O_3	.13	.001	.....
FeO	10.46	.145	11.73
MnO	.18	.002	.08
NiO	.12	.001	.....
MgO	21.79	.545	21.01
CaO	7.41	.132	6.17
Na_2O	1.33	.022	1.15
K_2O	.28	.003	.58
H_2O-	.04	....	1.62
H_2O+	.37	....	
P_2O_5	.11	.001	.15
CO_2	None	....	.....
SO_3	None	....	.....
BaO	None	....	.....
SrO	None	....	.....
ZrO_2	None	....	.....
	100.53		100.00
Sp. gr.	3.001		

Calculated Norm of 1.	
Orthoclase	1.67
Albite	11.53
Anorthite	13.90
Diopside	17.48
Hypersthene	17.06
Olivine	31.22
Ilmenite	3.50
Magnetite	3.25
Chromite	.22
Apatite	.31
Water	.41
	100.55

1 Porphyritic gabbro of the Uwekahuna laccolith.
1a Molecular proportions in 1.
2 Average analyses of three typical wehrlites.

Using the chemical analysis and the Rosiwal optical method, the minerals have been calculated to form the following weight percentages:

Olivine	40.0
Augite	31.0
Labradorite	27.0
Magnetite and ilmenite	1.7
Apatite	.3
	100.0

In the Norm classification the rock falls in the domagnesic subrang, wehrlose, in the permiric section, wehrliase, permirlic rang, wehrlase, and section hungariare, of the dofemane order, hungarare.

According to the accepted Mode classification the rock is an ultra-femic porphyritic olivine gabbro or gabbro porphyrite. The analysis is very similar to the average of three typical wehrlites entered in Part II of Osann's *Beiträge zur chemischen Petrographie*. See column 2 of the accompanying Table I.

Ultra-femic olivine basalt, flow of 1852.—Following the trail from the Volcano House to Mauna Kea, the writer crossed the lava which, in 1852, flowed out on the Hilo slope of Mauna Loa. The trail traverses this lava at the 6,100-foot contour (see locality "2" in Fig. 1), where the flow is about 1.5 kilometers in width. The lava is of the aa or block type and much work with sledge hammers was necessary to make a trail passable even for the hardy pack-animals of the island. The broken rock is, of course, quite fresh, and its numerous olivine phenocrysts, of unusually great size and of beautiful color and brilliance, made a remarkable effect for the eye as one walked or rode over the lava. The development of phenocrystic olivine is greater in this flow than in any other seen by the writer during several hundred miles of travel in Hawaii.

The hand-specimens of the lava have a dark-gray, lithoidal ground-mass, in which the abundant, bright yellowish-green olivines are conspicuously set. As usual with the aa type of lava, the gas pores are large and irregularly distributed through the rock. They were elongated and flattened during the flow of the stiffening lava and the longer diameters of the pores reach three or more centimeters in length. The idiomorphism of the olivine is often manifest to the unaided eye, and is still more evident under the microscope. The individual crystals are often more than one centimeter in diameter. No other mineral is phenocrystic.

The microscope shows a rather surprising contrast in the grain of the ground-mass, which is of diabasic structure, with thin tables of plagioclase, seldom over 0.1 mm. in length, separated by augite granules of even smaller diameters. Magnetite and prob-

ably ilmenite form the only other visible constituents, though a little apatite must occur. No glass and no sulphide mineral could be found in the ground-mass.

The olivine includes a little magnetite, in small euhedral and anhedral crystals. A few brown, roundish inclusions may be glass. In thin section the olivine is nearly colorless with a gray tinge. It was easily isolated and then freed of impurities except for the minute inclusions described. Its analysis, by Mr. Steiger, gave the following result:

		Mol.	Calculated Composition	
				Per cent
SiO_2	40.42	.670	Forsterite	82.29
TiO_2	.08	.001	Fayalite	15.94
Al_2O_3	.32	.003	Tephröite	0.20
Fe_2O_3	.15	.001		
Cr_2O_3	.18	.001		98.43
FeO	11.44	.159	Anorthite	0.97
MnO	.10	.001	Magnetite	0.23
NiO	.34	.005	Ilmenite	0.15
MgO	47.08	1.168	Chromite	0.22
CaO	.23	.004	NiO	0.34
	100.34			1.91
Sp. gr.	3.369		Grand total	100.34

So far as known to the writer, this is the only total analysis of any Hawaiian olivine yet made. Penfield and Forbes found 10.3 per cent of FeO in olivine collected by J. D. Dana on the southeastern shore, south of Hilo. The optical angle (2V) for this mineral was calculated to be 91° 2′, and the authors found that chrysolites containing about 12 per cent of FeO show a value of 90° for 2V in yellow light.[1] The olivine now described has 11.44 per cent of FeO, and hence it would be extremely difficult to be quite certain whether the mineral is positive or negative. No special work has been expended in the attempt to determine that point.

The minute plagioclase tables of the ground-mass gave maximum extinctions corresponding to the mixture Ab_{45} An_{55}. The augite is pale, practically colorless in thin section, and has no noteworthy

[1] S. L. Penfield and E. H. Forbes, *Amer. Jour. Sci.*, I (1896), 133

peculiarities. A study of the chemical and mineralogical analyses showed that it must be rich in FeO and relatively poor in MgO. The magnetite and ilmenite are abundant in the ground-mass.

Mr. Steiger's analysis of the rock gave the proportions shown in Table II.

TABLE II

	1	1a
SiO_2	48.57	.810
TiO_2	1.48	.019
Al_2O_3	10.51	.103
Fe_2O_3	2.19	.014
Cr_2O_3	.10	.001
FeO	9.45	.132
MnO	.16	.001
NiO	.08	.001
MgO	17.53	.438
CaO	8.06	.144
Na_2O	1.59	.026
K_2O	.34	.004
H_2O-	.10	....
H_2O+	.37	....
P_2O_5	.19	.001
CO_2	None	....
	100.72	
Sp. gr.	3.065	

Calculated Norm	
Orthoclase	2.22
Albite	13.62
Anorthite	20.29
Diopside	15.11
Hypersthene	23.98
Olivine	18.49
Ilmenite	2.89
Magnetite	3.25
Apatite	.31
Water	.47
	100.63

1 Ultra-femic olivine basalt, lava flow of 1852.
1a Molecular proportions in 1.

Using the Rosiwal method, checked by the analyses, the Mode (weight percentages) was calculated to be:

Olivine	32.0
Augite	27.0
Labradorite	35.7
Ilmenite	2.5
Magnetite	2.5
Apatite	.3
	100.00

Assuming the probable values of the specific gravity for each mineral, the specific gravity of the rock was calculated to be 3.16, which agrees satisfactorily with the actual value, 3.065, found by the proper weighing of coarse powder of the rock.

In the Norm classification the rock enters the hitherto unnamed

domagnesic subrang, in the permiric section and permirlic rang of the dofemane order, hungarare. If a name for this type in the Norm classification is desired, the subrang may be called *hilose*, from the name of the chief port of the island, Hilo. The corresponding names for the rang-section and rang would be *hiliase* and *hilase*. The hitherto unnamed section of the order may be called *hawaiiare*.

According to the Mode classification the rock is an ultra-femic olivine basalt of an extreme type. In both chemical and mineralogical analyses it approaches the still more abnormal type represented in the Uwekahuna laccolith.

Andesitic basalt, upper slope of Mauna Kea.—On the eastern side of Mauna Kea, from the 6,000-foot contour to about the 12,000-foot contour, the abundant lava flows seem to be very uniformly composed of a rock species which is intermediate between typical olivine basalt and a true augite andesite. These lavas are almost entirely of the aa or blocky type; pahoehoe surfaces are only locally developed and, within the area described, seldom, if ever, show the perfection so often illustrated in Mauna Loa. Among the specimens collected, one taken at the 11,000-foot contour (see locality "3" in Fig. 1), 4,500 meters S 75° E of the summit of Mauna Kea, was selected for chemical analysis. Its description would doubtless apply, with but unimportant change, to the average lava of all this part of the great volcano.

The rock is dark gray, fresh, and strongly vesicular, again showing the great irregularity in the size and distribution of the vesicles, which is usual with aa lava. The only minerals microscopically visible in the dense ground-mass are a few phenocrysts of yellowish-green olivine and tabular plagioclase, with maximum diameters of 2 mm. and 3 mm. respectively. In thin section a few idiomorphic phenocrysts of augite, reaching 1 mm. in length, are to be seen. Estimates made by the Rosiwal method show that the olivine phenocrysts form no more, or little more, than one per cent of the rock by weight, and that the augite phenocrysts occur in about the same proportion. The very abundant plagioclase phenocrysts have cores averaging about $Ab_1 An_1$ in composition. They are often surrounded by a very thin shell of oligoclase

averaging $Ab_7\,An_3$, as indicated by zero extinction on (010). That shell is surrounded by a still thinner, outermost shell, which gives an extinction of about $+5°$ on (010) and is either a more acid oligoclase or else orthoclase.

The ground-mass has a pilotaxitic to diabasic structure and consists of plagioclase, augite, and magnetite, each in high proportion. A few round granules of olivine may also be discerned. The plagioclase is often zoned, with a somewhat larger relative development of the acid shells. Again, the outermost shell may, in many cases, be alkaline feldspar, but the very fine grain prevents its actual demonstration. No sulphide mineral was visible in the rock.

Mr. Steiger's analysis yielded the result shown in column 1 of Table III.

TABLE III

	1	1a	2
SiO_2	49.73	.829	49.19
TiO_2	3.05	.038	1.72
Al_2O_3	16.39	.161	14.02
Fe_2O_3	7.58	.048	5.62
FeO	3.98	.056	8.68
MnO	.23	.003	.54
MgO	4.06	.101	6.42
CaO	7.17	.128	9.10
Na_2O	4.12	.066	3.24
K_2O	1.93	.020	1.04
H_2O-	.81	....	} .74
H_2O+	.54	....	
P_2O_5	.84	.006	.28
CO_2	None	....	.....
BaO	.03	....	.....
SrO	None	....	.....
NiO	.04	....	.....
Cr_2O_3	None	....	.....
ZrO_2	.03	....	.....
SO_3	None	....	.....
S	None	....	.....
	100.53		100.59
Sp. gr.	2.911		

Calculated Norm of 1	
Quartz	1.86
Orthoclase	11.12
Albite	34.58
Anorthite	20.85
Diopside	6.78
Hypersthene	6.80
Ilmenite	5.78
Magnetite	4.87
Hematite	4.32
Apatite	1.86
Water, etc.	1.45
	100.27

1 Andesitic basalt, lava flow at 11,000-foot contour of Mauna Kea.
1a Molecular proportions in 1.
2 Average composition of normal Hawaiian basalt.

By the Norm classification the rock enters the dosodic subrang, andose, in the alkalicalcic rang, andase, of the dosalane order, germanare.

According to the Mode classification, it is an andesitic basalt, transitional in type between olivine basalt and augite andesite. Its specific gravity was determined on a specimen which had been coarsely powdered to avoid an error due to the porosity of the rock. For comparison the calculated average for the basalt of Hawaii is given in column 2.

Trachydolerite of summit flows, Mauna Kea.—Brigham and others long ago noted the occurrence of "clinkstone" at the top of Mauna Kea, and the present writer had opportunity to make some study of this rock in place during the 1909 reconnaissance. Near the 13,000-foot contour, he found several flows of lava of much lighter color than the staple olivine basalts of Hawaii, or than the abundant andesitic basalt just described. These flows all seem to be short, generally less than one kilometer in length. Their terminal scarps have been little affected by frost or other weathering agents, and the steepness of these scarps indicates a notable degree of viscosity during the outflow. In some cases these flows could be seen to have emanated from the fissures in the summit cinder-cones. Though the pyroclastic material of the cones is generally altered (to deep brown and red tints), it appears to be chemically identical with that composing the always fresh, light-colored flows.

The "clinkstone" habit is due largely to a noteworthy lack of vesicles in the lava. Though some large gas-pores always occur in the thin surface shell of each flow, its interior is often nearly or quite free from even small pores. This homogeneity of the rock is, doubtless, chiefly responsible for the extremely sonorous, metallic sound given out when the lava is broken by the hammer.

For special examination, typical specimens were taken from a flow which issued from the eastern flank of the cinder-cone named "Poliahu" on the government map, at a point about 350 meters north of the summit pond. The description of the lava may be based on one specimen, which has been chemically analyzed.

The rock is of a fairly light, slate-gray color, is non-porous, very dense, but holocrystalline. A few thick tables of plagioclase, from 1 mm. to 2 mm. in length, represent the only constituent determi-

nable to the unaided eye. There is merely a hint at flow-structure, registered in a rude parallelism of these phenocrysts.

Under the microscope it is seen that a few, small, anhedral olivines, and somewhat more numerous augite crystals—none, in either case, surpassing 1 mm. in greatest diameter—are to be added to the abundant plagioclase (averaging labradorite, $Ab_1 An_1$) in the list of phenocrysts.

The ground-mass shows a confused crystallization of augite, magnetite, and apatite, in a dominant felt of feldspar. A few grains of an allanite-like mineral, pleochroic in tones from deep brown to pale greenish-brown, form the only other accessory material. No sulphide is visible in thin section. Most of the ground-mass feldspar is plagioclase—acid labradorite or basic andesine—twinned on the albite law. Another feldspar arranged interstitially in relation to the plagioclase has the low double refraction and lack of twinning characteristic of orthoclase. This mineral occurs in such minute individuals that a full demonstration of its nature has not been possible. Many of the labradorite phenocrysts are surrounded with shells of alkaline feldspar with extinctions on (010) ranging from $+5°$ to $+9° 30'$, suggesting orthoclase and soda-orthoclase, and it is very probable that both of these represent the last product of crystallization in the ground-mass. The total alkaline feldspar does not form much more than 15 per cent of the rock by weight.

Mr. Steiger's analysis of this rock gave the proportions shown in col. 1 of Table IV.

By the Norm classification the rock is to be referred to andose, the same subrang as that calculated for the andesitic basalt just described. According to the Mode classification, this rock, containing an essential amount of alkaline feldspar, is best included among the trachydolerites, as defined by Rosenbusch, though near the basaltic end of that series. In column 2 of Table IV the average of the 34 analyses of trachydolerites, named as such in the last edition of Rosenbusch's *Elemente der Gesteinslehre*, is given for comparison. Column 3 gives Lyons' analysis of a more alkaline, less femic, trachydoleritic type from the neighboring volcanic pile in Kohala.[1]

[1] A. B. Lyons, *Amer. Jour. Sci.*, CLII (1896), 424.

Lherzolitic nodules in the summit lavas of Mauna Kea.—The chief difference between the andesitic basalt and the trachydolerite is mineralogical; orthoclase is an essential constituent in the latter, and has wholly, or almost wholly, failed to individualize in the basalt. The two types are almost alike chemically. They also resemble each other in carrying rather numerous ultra-femic nodules of all sizes up to 10 cm. in diameter. These are always rounded and usually roughly spherical, of coarse grain, and of a

TABLE IV

	1	1a	2	3
SiO_2	50.92	.849	49.20	58.06
TiO_2	2.55	.032	1.68	1.88
Al_2O_3	17.59	.173	16.65	18.21
Fe_2O_3	3.80	.024	4.76	4.87
FeO	6.69	.093	5.36	2.01
MnO	.20	.001	.55	.36
MgO	3.90	.097	4.43	1.59
CaO	6.97	.125	7.74	3.29
Na_2O	4.28	.069	4.54	6.12
K_2O	1.86	.020	3.19	2.75
H_2O-	.35	....	1.30	.....
H_2O+	.79	....		.....
P_2O_5	.40	.003	.60	.65
CO_2	None	....	.....	.....
NiO	None	.....	.....	.....
Cr_2O_3	None	....	.....	.....
CuO, etc.	.....	.....	.....	.20
	100.30		100.00	99.99
Sp. gr.	2.761			

Calculated Norm of 1	
Orthoclase	11.12
Albite	36.16
Anorthite	23.35
Diopside	6.98
Hypersthene	7.21
Olivine	2.98
Ilmenite	4.86
Magnetite	5.57
Apatite	.93
Water	1.14
	100.30

1 Trachydolerite, lava flow at 13,000-foot contour on Mauna Kea.

1a Molecular proportions in 1.

2 Average of 34 analyses of trachydolerites named as such in the third edition of Rosenbusch's *Elemente der Gesteinslehre.*

3 "Andesite" from Waimea, Kohala district, in northwestern Hawaii.

dark green or brownish-green color. They seem to be rather uniformly composed of dominant olivine, much diallage, subordinate or accessory plagioclase, and a little magnetite or ilmenite. Apatite has not been demonstrated in thin section.

The nodules occur in the trachydolerite of the cinder-cones as well as of the adjacent flows. In a few cases observed, the nodules of the cinder-cones formed ellipsoidal bodies without any adhering trachydolerite, as if each of these nodules represents a solid mass exploded out of the vent and freed from liquid magma by the

violence of the explosion. More generally, the nodules occur in projectiles largely composed of the normal trachydolerite. The specific gravity of one ellipsoidal nodule about 8 cm. in length was found to be 3.316; it is almost entirely free from feldspar.

The nodules inclosed in lava are best displayed in the frost-riven felsenmeer surrounding the summit pond. One of these was sectioned and specially studied. The plagioclase was found to have the composition of acid anorthite, $Ab_1 An_9$. A few small tables of the feldspar and rare granules of olivine are inclosed in the diallage, but in general, the anorthite is interstitially developed between the olivine and diallage crystals, which seem to have crystallized nearly simultaneously and after the iron ore. The pyroxene is much more often idiomorphic than is the olivine. The specific gravity of this nodule is 3.111.

The Rosiwal method afforded the following estimate of its weight percentages:

Olivine	62
Diallage	26
Anorthite	11
Magnetite and ilmenite	1
	100

Assuming the olivine to have the same composition as the olivine in the lava flow of 1852, and the diallage to have the average composition of basaltic augite,[1] the nodule was calculated to have, approximately, the composition shown in column 1 of Table V.

TABLE V

	1	2
SiO_2	43.4	43.78
TiO_2	.3	.12
Al_2O_3	5.5	5.02
Fe_2O_3	1.5	5.18
FeO	8.8	4.77
MgO	32.8	33.08
CaO	7.4	6.62
Na_2O	.3	1.06
$MnO+K_2O+P_2O_5$	....	.37
	100.0	100.00

[1] See *Journal of Geology*, XVI (1908), 410.

Column 2 gives the average composition of four typical lherzolites.[1] In spite of any uncertainties as to the exact compositions of the femic minerals, it is clear that the nodule is, chemically, a lherzolite.

The writer believes that these nodules are not exotic, but represent segregations in their respective magmas just as truly as do the olivine phenocrysts. Easy transitions in size are to be found, in the field, between large, single phenocrysts of olivine and the largest olivine nodules observed.

Notes on other lava flows, studied microscopically.—On the trail from the Volcano House to Mauna Kea, at about the 6,000-foot contour (see Fig. 1), the flow of 1880–81 was found to be olivine basalt of the pahoehoe type. The adjacent flow of 1855 is similarly composed but has local aa phases. Still farther north the trail crosses the "ancient flow" shown on the government map (marked "ancient" in Fig. 1); this is an olivine basalt with typical aa habit. At the wagon-road between Waimea and Kailua, the great flow of 1859 is an olivine-poor to olivine-free basalt with both aa and pahoehoe phases.

Projected blocks at Kilauea and Hualalai.—E. S. Dana has already described the common, basaltic types of rock represented in the solid projectiles thrown out in the rare explosions which have occurred at Kilauea.[2] The present writer has made a microscopic examination of seven different specimens of the projectiles sampled at intervals along the edge of the Kilauean sink from Uwekahuna to Kilauea Iki. All of them are holocrystalline and they are non-vesicular or else nearly free from pores. In the coarser blocks the pores are true miaroles, into which the feldspar and augite, showing crystal facets, have grown. The rock species included in this small collection are: basalt poor in olivine; typical olivine diabase; olivine-free diabase; and a typical, relatively coarse-grained olivine-free gabbro.

Of these, the gabbro is the only type worthy of special remark. It composes several of the projectiles occurring on the road from the Volcano House to Kilauea Iki, near Waldron's Ledge. The

[1] See *Proc. Amer. Acad. Arts and Sciences,* XLV (1910), 226.

[2] See J. D. Dana, *Characteristics of Volcanoes* (New York, 1891), 344.

visible blocks are all angular, quite fresh, and 20 to 50 cm. in greatest diameters. No olivine is visible in the fairly dark-gray, granular rock, either in the field or under the miscroscope. The essential constituents are labradorite, Ab_2 An_3, and a strongly tinted, greenish-brown, non-pleochroic augite, with an unusual amount of iron ore, probably ilmenite. Apatite in needle form is very abundant; therein this rock contrasts with nearly every Hawaiian rock so far studied in thin section. The stout augite prisms, which lack the diallage parting, reach 4 mm. in length; the thick tables of labradorite are often 5 mm. in length and the plates of ilmenite measure 1 mm., or less, to 5 mm. in length. The structure of the rock is not basaltic or diabasic, but typically hypidiomorphic-granular.

On the summit of Hualalai the writer sampled three projected blocks which occur in a thin pyroclastic deposit veneering this lava-formed (olivine-basalt) volcano. Two of them are holocrystalline equivalents of the normal olivine basalt of the island. The third is a coarsely granular rock almost identical in composition and grain with the type forming the laccolith at Uwekahuna; it is an ultra-femic gabbro, with high idiomorphism in the abundant olivine.

Average composition of Hawaiian basalt.—Of the extant analyses of the basalts from the main island, nineteen, which were made from fresh and typical material, have been selected for the purpose of computing the average composition of the dominant rock type of the island. Most of these analyses are quoted in C. H. Hitchcock's *Hawaii and Its Volcanoes* (Appendix D). Ten are taken from O. Silvestri's paper in the *Bolletino del R. Comitato Geologico Italiano* (XIX [1888], 185); four from E. Cohen's paper in the *Neues Jahrbuch für Mineralogie*, etc. (1880; II, 23); and four from A. B. Lyons' paper in the *American Journal of Science* (II [1896], 424). Mr. Steiger's analysis of the 1852 flow and his analysis of the chemically similar porphyry forming the small laccolith at Uwekahuna, Kilauea, are also included, making twenty analyses in all.

The calculated average is shown in the first column of Table VI, where the second column gives the writer's result in averaging

198 analyses of fresh basalts taken from Osann's great compilation for the world (analyses published between 1884 and 1900).

TABLE VI

	Average Hawaiian Basalt	Average World Basalt
SiO_2	49.19	49.06
TiO_2	1.72	1.36
Al_2O_3	14.02	15.70
Fe_2O_3	5.62	5.38
FeO	8.68	6.37
MnO	.54	.31
MgO	6.42	6.17
CaO	9.10	8.95
Na_2O	3.24	3.11
K_2O	1.04	1.52
H_2O	.74	1.62
P_2O_5	.28	.45
	100.59	100.00

The close correspondence of the two averages is obvious at a glance. In fact, it has been found that the greater the number of reliable analyses included, the nearer the Hawaiian average approaches the world average. Though perfect averages might show the former to be slightly the more femic of the two, it is certain that the staple igneous type in the mid-oceanic Hawaii are chemically very similar to the average basaltic magma poured out on the continental plateaus.

THEORETICAL CONSIDERATIONS

Origin of the ultra-femic types.—In columns 1 and 2 of Table VII the analyses of the Uwekahuna laccolith and of the 1852 lava flow are respectively entered. Column 3 gives the mean of these two analyses. Column 5 gives the average analyses of four typical lherzolites, calculated as water-free. Column 6 shows the calculated composition of the average Hawaiian basalt, while column 4 gives the mean of columns 5 and 6.

A comparison of the markedly similar columns 3 and 4 suggests that the ultra-femic magmas of the island are due to the mixture of a large amount of the ferromagnesian and cafemic (calcium-iron-magnesium) constituents of the basalt with the average basalt itself, though, of course, not necessarily in absolutely equal pro-

portions for the two parts of the mixture. Such a mixture could occur in the main volcanic vents at great depth, provided that the ferromagnesian and cafemic molecules settled down from the magma in the upper part of the vent, where gravitative differentiation was taking place.

This explanation of the ultra-femic phases is favored by the consideration that no fact in the field relations opposes the assumption of a very deep, direct source for these heavy magmas. The flow of 1852 emanated from a fissure in Mauna Loa, about 1,300 meters below the top of the main conduit of the island; and the laccolithic body exposed in the wall of Kilauea is 3,000 meters

TABLE VII

	1 Laccolithic Porphyry	2 Flow of 1852	3 Mean of 1 and 2	4 Mean of 5 and 6	5 Average Lherzolite	6 Average Hawaiian Basalt
SiO_2	46.59	48.57	47.58	46.65	43.78	49.19
TiO_2	1.83	1.48	1.66	.92	.12	1.72
Al_2O_3	7.69	10.51	9.10	9.52	5.02	14.02
Fe_2O_3	2.20	2.19	2.20 } 12.15	5.40 } 12.12	5.18	5.62
FeO	10.46	9.45	9.95 }	6.72 }	4.77	8.68
MnO	.18	.16	.17	.30	.06	.54
MgO	21.79	17.53	19.66	19.75	33.08	6.42
CaO	7.41	8.06	7.74	7.86	6.62	9.10
Na_2O	1.33	1.59	1.46	2.15	1.06	3.24
K_2O	.28	.34	.31	.67	.30	1.04
H_2O	.41	.47	.44	.37	.....	.74
P_2O_5	.11	.19	.15	.15	.01	.28
Cr_2O_3 etc.	.25	.18	.21	.....	.....	.....
	100.53	100.72	100.63	100.46	100.00	100.59

below the same level. In either case, the level in the conduit where it was tapped to form the erupted body may have been several kilometers still lower down in that conduit.

Origin of the less femic types.—The hypothesis that the ultra-femic rocks represent the products of mixture of the average basalt with the ferromagnesian and cafemic substances (more specifically the molecules represented in the phenocrysts of the normal basalt) settled down from higher levels in the main Hawaiian vent, implies that more salic and more alkalic magma is formed at those higher levels. According to the thoroughness of the gravitative differentiation, the less dense magmas would vary in the degree in which

they would be more salic and alkalic than the parent basalt. As a matter of fact, a goodly number of such derived magmas seem to be represented in Hawaii. Table VIII, columns 2–6, shows the chemistry of the principal types to which this mode of origin may be, at least tentatively, ascribed.

TABLE VIII

	1	2	3	4	5	6
SiO_2	49.19	49.73	50.92	58.06	61.64	62.19
TiO_2	1.72	3.05	2.55	1.88	.....	.37
Al_2O_3	14.02	16.39	17.59	18.21	.....	17.43
Fe_2O_3	5.62	7.58	3.80	4.87	.....	1.65
FeO	8.68	3.98	6.69	2.01	.....	2.64
MnO	.54	.23	.20	.36	.....	.32
MgO	6.42	4.06	3.90	1.59	.....	.40
CaO	9.10	7.17	6.97	3.29	.....	.86
Na_2O	3.24	4.12	4.28	6.12	.....	8.28
K_2O	1.04	1.93	1.86	2.75	.....	5.03
H_2O	.74	1.35	1.14	.....	.....	.53
P_2O_5	.28	.84	.40	.65	.....	.14
NiO, etc.	.....	.10	.....	.20	.....	.09
	100.59	100.53	100.30	99.99	.....	99.93
Sp. gr.	.....	2.911	2.761	.....	.....	2.627††

†† Determined from hand-specimen collected by the writer. All three rocks for which specific gravities are given, are holocrystalline.

1 Average analysis of twenty basaltic types in Hawaii.

2 Andesitic basalt of Mauna Kea.

3 Trachydolerite of summit, Mauna Kea.

4 "Andesite" (trachydolerite) of Waimea, Kohala district (analyzed by A. B. Lyons, *Amer. Jour. Sci.*, II [1896], 424).

5 "Augite Andesite from the Sandwich Islands" (silica determined by E. Cohen, *Neues Jahrbuch für Mineralogie, etc.* [1880; II, 38]).

6 Phonolitic trachyte of Puu Anahulu (described by W. Cross, *Journal of Geology*, XII [1904], 510).

On p. 53 of the paper by Cohen, for which the reference has been given, it is stated that in the rock collection there described, four other occurrences of "typical augite andesites" in Hawaii are represented. Two of the specimens were taken on Mauna Kea; the other two were collected on this island, but the labels failed to give their exact localities. No analyses were made of these specimens, but, of course, one may trust Cohen's well-known skill in diagnosis and place all four rocks among the more salic types of Hawaii.

From the table it seems clear that the strongly alkaline trachyte

of Puu Anahulu and the "andesite" of Waimea are consanguineous and that transitional types connect them with the distinctly subalkaline, normal basalt of the island. The steady decrease of the iron oxides, magnesia, and lime, and the corresponding increase in silica, alumina, and alkalies are as systematic as could be expected in a syngenetic series derived by the process of differentiation already in part described.

The norms calculated for the analyzed types tell the same story. They are summarized in the form here given:

	Average Hawaiian Basalt	Andesitic Basalt of M. Kea	Trachydolerite of M. Kea	Andesite of Waimea	Trachyte of Puu Anahulu
Salic........	53.94	68.41	70.63	85.09	86.74
Femic.......	45.76	30.41	28.53	14.75	12.45

Calculation shows that the alkalic members of the series were probably not formed by a mere subtraction of ferromagnesian and cafemic, phenocrystic material from the normal basaltic magma. On the other hand, a positive addition of the alkalies seems to have occurred when the more silicious types were developed.

The concentration of the alkalies in the upper part of an initially basaltic vent may conceivably be due to two principal causes. In the first place the feldspathic or feldspathoid matter of the basalt might individualize in liquid phases or as plastic or rigid crystals, and, because of the low density of any of these phases, rise in the magma column, just as the individualized olivine or augite (in liquid or solid phases) must sink. Or, secondly, the volcanic vent may become temporarily enriched in emanating gases, which, as they rise, bring the alkalies with them in loose combination.

Of these two possible causes the partial control by rising volatile substances seems to be specially clear in intrusive bodies. The writer has suggested that most of the alkaline rock types have been derived from subalkaline magma through the solution of limestone or other carbonate-bearing sediments.[1] Thereby the subalkaline magma is not only fluxed and so prepared for drastic

[1] *Bulletin Geological Society of America*, XXI (1910), 87–118.

differentiation, but the carbon dioxide introduced from the sediment carries the alkalies with it as the gas rises through the magma. An instructive series of experiments by Giorgis and Gallo bear on this suggestion. They mixed the powders of various recent Vesuvian lavas with water, and passed a current of carbon dioxide through each mixture for a period of two months. Analyses showed that the powders lost, on the average, 37 per cent of the soda originally contained, the remaining constituents being but little altered in amount.[1] At high temperatures the upward transfer of the alkali would presumably be much more rapid.

In the case of the Puu Anahulu trachyte or in that of the Waimea "andesite," the principal factor in the differentiation may have been the solution of coral or foraminiferal limestones, such as are known to be interbedded with the older lavas of the archipelago. That the normal magma of the archipelago has been locally affected by such solution is suggested by the occurrence of melilite and nephelite in the basalts of Maui and Oahu, the melilite indicating an excess of lime and the nephelite showing such desilication of the salic part of the magma as is expected when it dissolves foreign lime. The carbon dioxide entering the primary basaltic magma because of this solution of sedimentary rock would belong in the "resurgent" class of emanations. A special concentration of juvenile carbon dioxide in a basaltic vent would, in an analogous way, tend to concentrate the alkalies of the basalt at the top of the vent.

This hypothesis, that the decidedly alkaline rocks of Hawaii have been derived from the normal, subalkaline basalt through gravitative differentiation in the volcanic conduits, is supported by the intimate field-association of the two classes of rocks, and by the fact that the alkaline bodies are all of very small volume as compared with the known mass of normal basalt in Hawaii. The first-mentioned relation is obvious; the second is already clear, even though the island has been covered only by reconnaissance journeys. It is practically certain that the trachyte of Puu Anahulu and vicinity, the most salic type and one very conspicuous in the field, can be exposed at but very few and small

[1] G. Giorgis and G. Gallo, *Gazetta* (1906) [I], 137.

areas at the present surface of the island. As expected on the hypothesis, the alkaline types more nearly approximating the average basalt in composition are much more voluminous than the extreme phonolite-trachyte member of the series. In Mauna Kea, at any rate, the trachydoleritic representative of the alkaline species seems to be confined to the summit plateau of the volcano, that is, to the region where it should occur if it were due to the vertical differentiation of the basalt.

On the other hand, the dominant rocks on the broad summits of Mauna Loa and Hualalai, and of Haleakala, in Maui, are normal basalts, often rich in phenocrystic olivine.[1] There is no doubt that the conditions were unfavorable to important differentiation during most of the time engaged in the building of these giant volcanoes. Similarly, the lava of the active vent at Kilauea is basaltic and apparently has always been of that normal composition.

One reason for this contrast with Mauna Kea in its latest stage is probably connected with difference of temperature, for the differentiation of any of the commoner earth magmas seems to take place only within a comparatively narrow temperature range occurring just above the "point" of solidification. That the average temperature of the latest Mauna Kea vents was actually lower than that characteristic of the active Mokuaweoweo on Mauna Loa is suggested: (*a*) by the smaller size of the pipes on Mauna Kea; (*b*) by the far greater abundance of pyroclastic material on Mauna Kea; and (*c*) the correlative high viscosity of the short, stubby flows on Mauna Kea. The latter were more viscous than the average flow on the summit of Mauna Loa, not merely or chiefly because of difference in chemical composition.

But a probably much stronger control is to be found in the

[1] E. S. Dana describes a group of "clinkstone-like basalts" (specific gravity, 2.82–3.00), free from olivine or very poor in it, which were collected at the summit of Mauna Loa. These may represent incipient differentiation even at Mokuaweoweo. Another, highly olivinic group of basalts (specific gravity 3.00–3.20) are, however, associated in great volume. (See J. D. Dana, *Characteristics of Volcanoes* [New York, 1891], p. 319.) The present writer found a similar variation in the basalts at the summit of Haleakala, which are cut by dikes of compact, olivine-free rock suggestively like the trachydolerite of Mauna Kea.

inhibiting convection which is so powerful in highly fluid columns like those of the active Mokuaweoweo or Kilauea. In a paper published in the current volume of the *Proceedings of the American Academy of Arts and Sciences*, the writer has indicated the probable cause of the very energetic stirring visible in the Kilauea lava column. The action is there called "two-phase convection," as it depends on vesiculation of the lava in depth. The gas-bubble phase is formed through supersaturation of the liquid with juvenile volatile matter. A small amount of vesiculation in depth must lend much buoyancy to the magma, which rushes up the conduit in periodic gushes; its place is taken by sinking magma that has been rendered more dense by the escape of its included gas at the surface. This type of stirring—incomparably more effective than thermal convection can be in such a column—keeps the vent open by transferring the abyssal heat to the zone of radiation; and as well, tends to prevent differentiation because of the continuous, thorough mixing of components in the magmatic column. A dormant state is introduced when the special supply of gas is largely exhausted. Then two-phase convection is slowed down, and if the other conditions permit, gravitative differentiation may affect the column more or less. Revival of activity is the result of a renewed concentration of juvenile gases rising into the conduit from the feeding magma chamber. The consequent strengthening of two-phase convection means a speedy remixing of the products of differentiation in the column. Hence, in such hot vents as those at Kilauea, Mokuaweoweo, or Matavanu, outflows of highly differentiated lavas are not to be expected.

When Mauna Kea was approaching extinction, its magmatic column or columns, characterized by increasing viscosity and perhaps less charged with juvenile gases, were less stirred by two-phase convection. In relative quiet they differentiated to a slight extent, giving a trachydoleritic type as the upper, salic pole. The gases became dissipated at the craters, and the effluent lavas of this latest phase of the volcanic pile are "clinkstones" because comparatively free of gas-pores. The explosions which formed numerous cinder-cones at the summit may have been due to the inhibition and superheating of meteoric

water, as well as to the latest, violent expulsion of the juvenile gases from the increasingly viscous magma.

Little is known of the detailed geology of the Kohala district, but the abundance of cinder-cones on the heights of this other great pile suggest a differentiation history resembling that sketched for Mauna Kea. However, the strongly alkaline "andesite" of Waimea, like the phonolitic trachyte of Puu Anahulu, may represent limestone-fluxing as a leading condition for such specially advanced differentiation of the basaltic magma.

Parallel differentiation in other oceanic islands.—Weber's recent study of the Samoan lavas, including those from Savaii, shows a remarkable similarity between them and the rocks of the Hawaiian group.[1] The types already found in Savaii and in the neighboring islands include: olivine basalt, olivine-poor basalt, andesitic basalt, trachydolerite, "Alkalitrachyt," trachyte, and phonolite. "Savaii" is said to be the Samoan equivalent of the name "Hawaii." By a curious coincidence the vent of Matavanu is, among vents now active, the most perfect known analogue to Kilauea; and the volcanic mechanism seems to be practically identical in these two archipelagoes. The writer entirely agrees with Weber as to the necessity of regarding the subalkaline and alkaline rocks of each island group as syngenetic. The parallelism in the magmatic histories of Savaii and Hawaii is shown even in details, for Weber described olivine-augite nodules in the feldspar basalt of Mauga Loa, a rock which in all respects recalls the nodule-bearing, andesitic basalt of Mauna Kea.

Among the leading effusive types in Tahiti are olivine basalt, olivine-free basalt, haüynophyre, phonolite, and picrite, the description of the last-mentioned rock resembling that of the analyzed 1852 flow in Hawaii. Although basalts compose most of Tahiti, this mid-Pacific island has also furnished nephelite syenites, theralites, essexitic gabbros, and tinguaites.[2] In the Solomon islands olivine basalt and augite andesite are associated with an

[1] M. Weber, *Abhandlungen Math-phys. Klasse, Kgl. Bayerischen Akademie der Wissenschaften*, XXIV (1909), 287.

[2] A. Lacroix, *Bulletin Société géologique France*, X (1910), 91–124.

augite trachyte which is suggestively like the phonolitic trachyte of Puu Anahulu in Hawaii.[1]

Reconnaissances in Kerguelen Island show the intimate association of olivine basalt, basalt bearing olivine nodules, trachyte, and phonolite. Basalts and alkaline trachytes are the known species composing Ascension Island. St. Helena shows dominant olivine basalt and olivine-free basalt, with haüynite basalt and phonolite.

Without citing other parallels among the oceanic islands, it is now clear that the repeated association of volcanic species, ranging from olivine basalt to phonolitic trachyte or true phonolite, is not accidental. In all essential respects the argument for the gravitative differentiation of the salic types from normal basalt seems as strong for the chief Samoan island as it is for the chief Hawaiian island. It is commonly assumed that the subalkaline basalt and the alkaline phonolite originate in separate primary magma chambers. That hypothesis becomes almost, if not quite, incredible to any unprejudiced observer of the imposing likeness in the evolution of these distant, deep-sea island groups.

SUMMARY AND CONCLUSIONS

The writer's 1909 traverses in Hawaii have led to the view that the average of the many extant, typical analyses of its basalts approximates very closely the composition of the real average of all the basalt exposed in the island. This average is almost identical with that calculated for the world's average basalt. While Mauna Loa and Hualalai are basaltic from base to summit, Mauna Kea is, in a sense, stratified. Up to about the 6,000-foot contour, the broad basal slopes of Mauna Kea are underlain by the normal olivine basalt. From that contour to the summit platform, about 6,000 feet higher, the dominant lava is a basalt, very poor in olivine and, in other respects also, approaching the composition of a basic augite andesite. At the top of the mountain are flows and cinder-cones largely consisting of a still less femic type, in which alkaline feldspar (orthoclase or soda-

[1] W. W. Watts, *Geological Magazine*, XXIII (1896), 358.

orthoclase) seems often to form an essential constituent. This type is best classed as a trachydolerite of basaltic affinities. Its chemical analysis is almost identical with that of a common phase of .the andesitic basalt, but, for some reason, alkaline feldspar did not crystallize from the latter magma. This arrangement of rock-species in Mauna Kea is explained as due to gravitative differentiation in the normal basaltic magma.

More pronounced splitting is registered in the highly alkaline trachydolerites and phonolitic trachyte occurring in the Kohala district and at Puu Anahulu and the neighboring Puu Waawaa. The development of these extreme types is tentatively ascribed to changes in the normal basalt by its solution of small quantities of sedimentary limestone cut by the respective lava conduits. No direct evidence for this hypothesis has been found; it is based on facts derived from the field and chemical relations of alkaline rocks throughout the world. Whether this hypothesis is correct or not, there can be little doubt that the alkaline rocks of Hawaii, Savaii, and other islands are as truly connected in a genetic way with the normal basalt, as ordinary aplite dikes are genetically connected with their respective granite batholiths. Such an origin for the Hawaiian alkaline rocks is rendered all the more probable because of their small relative bulk, and because of the perfect chemical transition which can now be shown between the normal basalt and the most salic of the alkaline types.

Further, a study of the olivine-pyroxene-anorthite segregations in the andesitic basalt and in the trachydolerite of Mauna Kea actually illustrates a stage of the differentiation. These nodules formed in the magma when its viscosity must have been enormous; else they would have rushed down into the conduit to levels where no summit eruption, of the small size represented in the flows and cones at the top of Mauna Kea, could have brought the nodules up again. It is almost certain that the settling-out of the olivine and pyroxene material (in solid or liquid phases) must have taken place at slightly higher temperatures, when the viscosity was much less. The residual magma must obviously become more alkaline in proportion to the degree of settling-out.

The ultra-femic material, sinking to great depth, where it

mixes with the hot, normal basalt, is subject to extrusion through lateral fissures which bring the deeper levels of the conduit into communication with the surface. Such is the preferred explanation for the ultra-femic olivine-basalt which emanated from Mauna Loa in 1852, and for the wehrlitic porphyry composing the Uwekahuna laccolith.

An explanation is offered for the apparently contradictory fact that gravitative differentiation is little evident in the thoroughly basaltic summit rocks of Mauna Loa and Hulalai, or in the material of the active vent at Kilauea.

As a result of studies in this and other fields, and in the general literature of petrology, the writer is inclined to the belief that all late pre-Cambrian and younger "alkaline" rocks are the result of differentiation within primary basaltic magma or within syntectic magmas formed by the solution of solid, generally sedimentary, rock in the primary basalt. The marvelously uniform composition of the basaltic magma issuing from countless fissures in every ocean basin as in every continental plateau, seems capable of explanation only on the premise that it forms the material of a continuous, world-circling substratum. The facts of geology suggest that this substratum was formed by an ancient liquation which took place when the globe was molten at its surface. This general conception became gradually clear to the writer during the genetic study of many intrusive bodies; it had been visualized in much the same form by that extraordinarily suggestive observer of the Hawaiian volcanoes, W. L. Green, whose *Vestiges of the Molten Globe*, Part II, first became known to the present writer in 1909. Not a single one of the myriad facts recorded in general petrography and geology definitely opposes this hypothesis, which, to the writer, seems to be the best working premise for a general philosophy of the igneous rocks.

Lastly, it appears from the accumulating results of geological work that the division of igneous rocks into "Atlantic" and "Pacific" races or groups is not warranted by the facts of distribution, nor by the requirements of sound petrogenic theory, nor by the needs of systematic petrography. In the heart of the Pacific basin, as in many regions along its borders, rocks of foyaitic,

theralitic, or other alkaline habit are already known, and the number of occurrences in that part of the earth is constantly growing. It may be quite true that alkaline rocks are more abundant on the Atlantic side of the globe—possibly because thick prisms of calcareous sediments are, in proportion to area, more developed in the Atlantic region—but it is yet more apparent that the overwhelming mass of the igneous rocks in the Atlantic region are subalkaline in type. The distinction of the two "Atlantic and Pacific races" (Sippen) is not only fallacious in the literal, geographic sense; it introduces an unnecessary pair of terms of quite elusive definition in place of the well-established, less nebulous terms "alkaline" and "subalkaline." The proved difficulty of making a clean-cut definition of the expression "alkaline rock" finds explanation in the theory that all late pre-Cambrian and younger alkaline rocks are of secondary origin, because derived from basalt or from its syntectics. According to this view, many transitional types should be found between the highly alkaline species and those low in alkalies; iron-clad definition becomes impossible.